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Efficiency Analysis of Elevator Aided Building Evacuation Using Network Model

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Abstract

Due to the reason that the number of occupants in high-rise building is usually very large, the evacuation process of the building would cost a lengthy time, which threats the life safety of the occupants under the circumstance of serious disaster such as fire. Thus to ensure the safety of occupants, different evacuation strategies have been proposed. One of the recently proposed strategies is that fire elevators should be used to aid evacuation so that the congestion level in the stairwell would be reduced. To explore the efficiency of elevator aided evacuation process, a network model for building evacuation is established in the present paper. Factors including the building plan component, the number of occupants and the configuration of the elevator status which affect the evacuation efficiency have been numerically investigated. A first principle for elevator aided evacuation has been summarized. Results also indicate that there is a top limit of the optimization process of the elevator aided evacuation.

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Keywords: elevator evaucaiton, stair evacuatoin, evacuation efficiency, performance based fire design.

1. Introduction

Ever since the '911' disaster, the evacuation process of high-rise buildings has attracted researchers from the disciplines of architectural engineering, fire protection engineering, building services and so on. For the reason that the occupancy of such complex building is relatively high, the number of occupants in the building is usually very large. As a result, the evacuation process costs intolerable long time [1-4].

To speed up the evacuation process of the high-rise buildings, different ways has been proposed. For example, refuge floor in high-rise building is usually required to be built by building codes as a temporary safety shelter to keep occupants away from the disasters such as fire [5]. Using this specific facility in the building, evacuation modes such as phased evacuation has been proposed [3, 4, 6, 7]. This kind of partially evacuation strategies can improve the evacuation efficiency. However, when disaster such as the '911' event happened, people in the building should all be evacuated. Thus elevator aided evacuation process seems to be optional. International building code (IBC) [8] recently allowed well-protected fire elevators to be used in building evacuation. To investigate the efficiency of elevator aided evacuation, a cellular automaton model has been built [3] by taking into account of the movement of the pedestrians and the elevators. It was found that elevator aided evacuation should be well-designed to archive an effective evacuation for high-rise buildings.

To explore the effect of different building component on the efficiency of building evacuation, in the present paper, the authors adopt another kind of model, i.e., the network model, to study the high-rise building evacuation process. Comparing to the cellular automaton models, the network model [9, 10] can be easily used to model the structure changes. It is assumed that evacuees in the building will first be evacuated to the refuge floor, where they will be further evacuated by stairwell or

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the elevator depending on the status of the elevators [5]. In this way, the effect of the number of the evacuees on each floor, the speed of the elevator as well as the capacity of the elevator can be discussed.

The rest of the present paper is organized as follows. In the 2nd section, a network model for a typical office building is constructed. Based on the network model, evacuation process has been simulated in section 3. Results of the simulation have also been discussed. In the last section, we briefly summarize the findings and emphasize the fire protection design issues of elevator aided evacuation.

2. Network model for building evacuation

2.1. Overview of the office building

For simplicity and without loss of generality, a 19-story office building is selected as an example to investigate the evacuation process of high-rise building. In this high-rise office building, there is one refuge floor, i.e., the 10th floor as required by the fire protection code for buildings in China. Occupants who move down to the refuge floor could continue their evacuation process by using the stairwell or by using an elevator on the refuge floor. Here in the present paper, there are four fire elevators serving the refuge floor and the ground floor, as shown in Fig.1(a). That is to say, the elevators only stop at the refuge floor and the 1st floor. Occupants entering into the elevator can be transported directly on the safety area on the 1st floor.

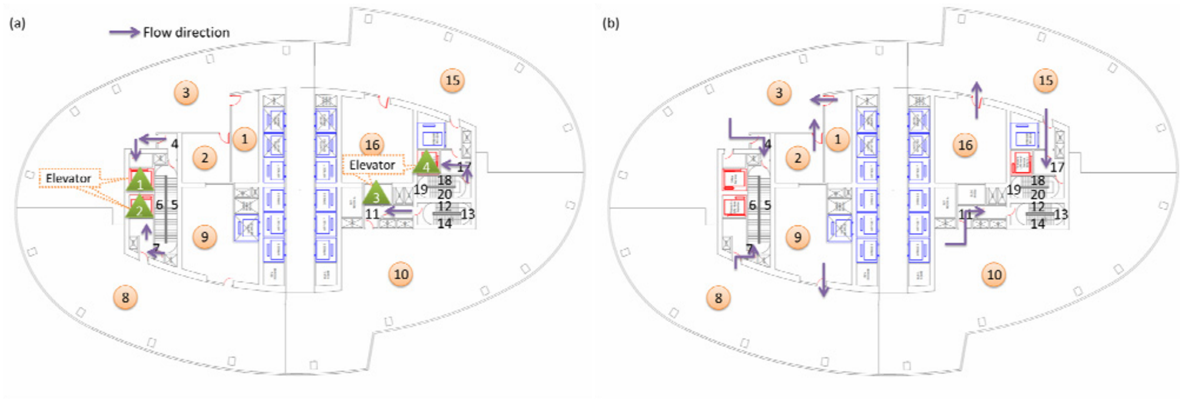

Fig. 1. Scheme of the (a) refuge floor and (b) normal office floor as well as the divided regions in the building.

The other floors except the refuge floor are used as offices and are named as normal floors. The building plan of these normal floors can be found in Fig.1(b). As can be found from Fig.1(b) that there are four fire compartments. Each of the fire compartments has an exit to the corresponding escape stairwell. It is assumed that occupants on each floor can only be egressed by the stairwell which locates in their corresponding fire compartment. After moving through a 1.2m wide exit door into the stairwell, the occupants will egress down along the stair to safety regions. Each floor has a height of 4m. Thus the occupants on the top floor as a result have to move down 72m to get to the safety region. It should be noted that each door in Fig.1(b) has a width of 1.2m. The width of the stair is also 1.2m.

The area of each floor is about 1,200 square meters. The designed number of occupants on each floor is 240. As a result there would be 60 people in each fire compartment. To explore the effect of the number of evacuees on the evacuation efficiency, it is firstly assumed that there are 240 and then 480 people on each floor to perform the following numerical simulations.

2.2. Network model construction

To build a network model for the high-rise building, each normal office floor is divided into 20 different regions, as shown in Fig.1(b). These regions can be modeled as nodes of a network. Each node has a capacity and an initial number of contents representing the number of occupants it can hold and the initial number of occupants in the corresponding region, respectively. During an evacuation process, the occupants egress from one region to another. This process is as a result modeled as content of a node flows along a link of the network to another node of the network. As can be found from Fig.1(b), the occupants' movement from one region to another region is confined by bottleneck such as doors, exits. Thus each link of the network has a flow capacity which is determined by the bottleneck capacity. It is further assumed that the number of occupants in each region, i.e., the node content, at the beginning of the evacuation follows Table.1 when the total number of pedestrian on each floor is 240. The capacity of each link of the network can be found in Table.2.

Table 1. Initial node content of the network model for the office building

Node*	Capacity	Initial content	Node*	Capacity	Initial content
WP1	50	5	LA13	9	0
WP2	50	5	SW14	14	0
WP3	700	50	WP15	700	50
LA4	27	0	WP16	100	10
SW5	30	0	LA17	27	0
SW6	30	0	SW18	10	0
LA7	27	0	LA19	9	0
WP8	700	50	SW20	10	0
WP9	100	10	EL1	20	0
WP10	750	60	EL2	20	0
LA11	27	0	EL3	20	0
SW12	10	0	EL4	20	0

*In this table WP, LA, SW and EL stands for work place, landing area, stairwell and elevator, respectively.

Table 2.Typical link capacity of the network model for the office building

Link specification*	Capacity/PED	Transit time/TP	Link specification*	Capacity/PED	Transit time/TP
LA4.1-DS1.1	6	2	SW6.2-LA4.1	6	3
LA7.1-DS2.1	6	2	WP10.2-LA11.2	6	2
LA11.1-DS3.1	6	2	LA11.2-SW12.2	6	3
LA17.1-DS4.1	6	2	SW12.2-LA13.2	6	2
WP1.2-WP3.2	6	2	LA13.2-SW14.2	6	1
WP2.2-WP3.2	6	2	SW14.2-LA11.1	6	2
WP3.2-LA4.2	6	1	WP16.2-WP15.2	6	2
LA4.2-SW5.2	6	2	WP15.2-LA17.2	6	3
SW5.2-LA7.1	6	3	LA17.2-SW18.2	6	3
WP9.2-WP8.2	6	2	SW18.2-LA19.2	6	2
WP8.2-LA7.2	6	1	LA19.2-SW20.2	6	1
LA7.2-SW6.2	6	1	SW20.2-LA17.1	6	2

*'-' in the table means 'move to' while '.2' means 'on the 2nd floor'. TP stands for time periods.

The network model for the office building shown in Fig.1 can be found in Fig.2. It should be pointed out that the elevators on the refuge floor locates near the lobby room, thus evacuees in the lobby room can enter into an elevator when the elevator is available. After entering into the car of the elevator, the evacuees would be taken directly down to the 1st floor. The speed of the elevator is denoted as v, while the capacity of the elevator car is denoted as N hereinafter.

The constructed model is then simulated with EVACNET4, which is developed by T. Kisko *et al*. in 1980s [10]. To be noticed, EVACNET4 only models elevators running on a specified and fixed schedule. The required input information includes the elevator travel time, the time of the first departure from a random location, and the elevator capacity. Given this information, EVACNET4 runs the elevator on the defined schedule. Occupants are carried down to the safety zones. For the sake of the simulation, each time period of the simulation is set to be TP=5s in the present study.

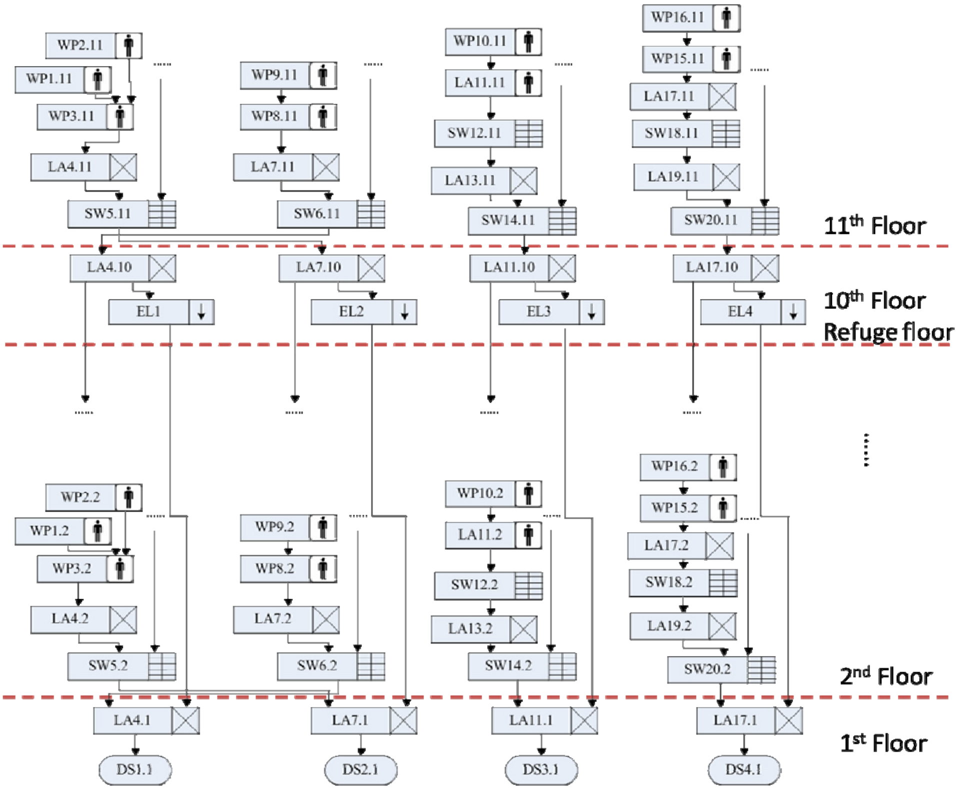

Fig. 2. Illustration of the network model for one normal office floor, the refuge floor and the 1st floor.

3. Results and discussion

Based on the network model for the office building in section 2, here in this section we perform numerical simulations to explore factors affecting the evacuation process.

3.1. Effect of number of occupants

It is firstly assumed that there are 240 people on each floor except the refuge floor and the 1st floor. Thus there are in total 4080 people in the building to be evacuated. When the elevators are forbidden to be used as a way of escape, those all occupants can only complete their evacuation by the stairs. Simulation of this kind of evacuation reveal that the clearance time for each floor increases with the decrease of the floor number, as shown in Fig.3. Here clearance time means that the last evacuee leaves the corresponding floor. It takes about 15min to evacuate all the occupants in the building to safety zones.

We then double the number of people to be evacuated to check the evacuation process. The clearance time curve for each floor of the building can also be found in Fig.3. Simulation results indicate that the total evacuation completes in less than 30min, which is a little smaller than twice the former total evacuation time. This phenomenon might results from the occupancy changes. For the former simulation, the occupancy is about 5m^2 per person while in the later one the occupancy is about 2.5m^2 per person. It should be noticed that the area of each floor is relatively large, occupants in the building can as a result move almost freely in the office area. That is also to say the initial evacuation process is relatively fast. Thus although the number of occupants is 2 times as large as the former case, the evacuees can still move almost freely, thus the time to be evacuated to the stairwell exits would be less than 2 times of the former evacuation time. After the moving into the stairwell, the pedestrian movement speed becomes lower than the movement speed in the work place. However, the density of the pedestrians in the stairwell for both of the simulated cases would be almost the same, thus the evacuation time for this period of evacuation would be equal to each other.

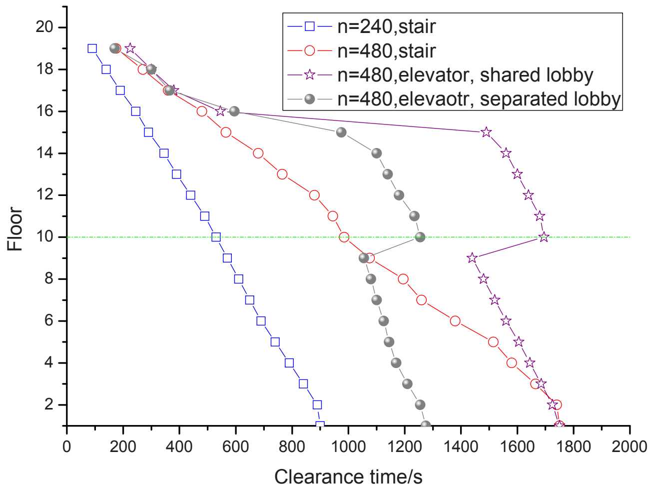

Fig. 3. Clearance time for each floor of the 19-story office building.

Further comparing the above two simulation cases it can also be found that the slope of the clearance time curve for those floors under the refuge floor costs becomes smaller. That is to say the evacuation process takes a relatively longer time for the lower level floors. This might due to the reason that evacuees accumulate in the lower section of the building thus the congestion level of the stairwell becomes much severe. The evacuation thus becomes slower.

3.2. Effect of elevator aided evacuation

When the elevators are allowed to be used to transport evacuees to the 1st floor, the evacuation simulation result can be found in Fig.3. It should be noticed that the number of people on each floor is assumed to be 480. The elevator speed here is set to be v=4m/s. Further considering the acceleration and deceleration process, it takes about 11s for the elevator to move from the refuge floor to the ground floor. After arriving at the destination, it takes about another 2s to open the door, and then let evacuees out or in. The elevator door close would take another 2s. Thus, the elevator has to spend about 15s, i.e., 3PT to complete a one way journey to the destination.

It should also be noticed that here in this case we assume the elevator can take at most N=20 people down to the ground floor in one trip. When we look at the simulation result of this kind of elevator aided evacuation process, it is interesting that the total evacuation time for this building is almost the same with the one when only stairs were used. It is even a shock that most of the floors have a longer clearance time. Analyzing the node content evolution reveals that the use of elevator on the refuge floor makes some pedestrian waiting. As can be found from Fig.1(a), the fire elevator and the emergency egress stairwell share a lobby room, thus the evacuees' waiting in the lobby room makes the stairwell much more congested. Meanwhile, the elevator speed is relatively low, thus the waiting behavior costs a lot of time, so the floor clearance time becomes longer. However, it should be noticed that although the clearance time for most of the floor becomes longer, the evacuation rate for this office building becomes larger than when no elevator is used, as shown in Fig.4. This is due to the reason that the elevator capacity is relatively larger and as a result more people can be evacuated out of the building per time period when compared with the stair pedestrian movement.

When we look back at Fig.1(a), it should be noticed that when those people move out of the elevators, they would firstly encounter those who move down from upper stairs using stairs, and then together they move out of the lobby to the final safety zone. When the lobby is nearly full, neither those who were transported to the ground floor nor those who used stairs to escape can enter into the lobby, they as a result have to wait until this lobby is empty. Thus to reduce the waiting time when perform elevator aided evacuation, the building plan for the elevator and the stair should firstly follow a principle, i.e., *the fire elevator and the stairwell should not use a shared lobby on the ground floor* when the elevator is allowed to evacuate people. According to this principle, hereinafter it is assumed that there is another landing area for each of the elevators. These landing areas also leads the evacuated people to a safety zone for each fire compartment.

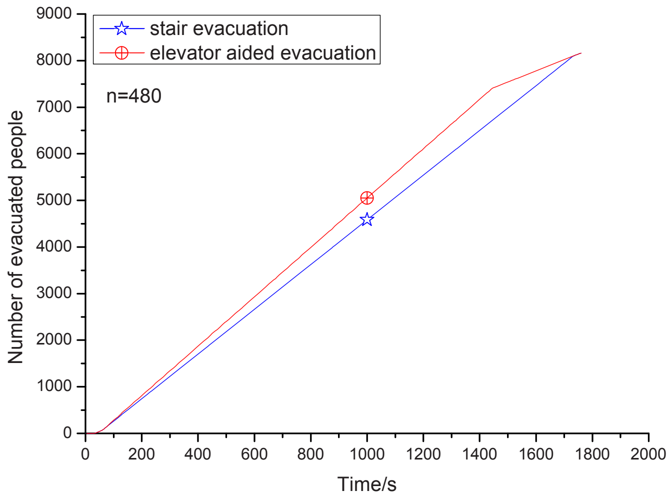

Fig. 4. Evacuation profile of the office building with and without the elevator aided evacuation.

Applying the above principle into practice, we perform simulation for the 4th evacuation case. As can be found in Fig.3, the evacuation time decreased a lot. The total evacuation can now complete in about 21min, which means the evacuation process has been improved, especially for those floors under the refuge floor. The slope of the clearance time for the lower section floors is also larger than the stair evacuation case. It should be noticed that for the floors above the refuge floor, the clearance time is still longer than the time when there is no elevator used. This feature is also resulted from the waiting induced congestion, as detailed above.

3.3. Effect of elevator configuration

To reduce the congestion levels for the floors above the refuge floor, we can use faster elevators or use larger capacity elevators. These two different elevator configurations will affect the evacuation process. For simplicity, here we double the elevator speed and then double the elevator capacity to investigate their influences. Simulation results of the corresponding cases can be found in Fig.5.

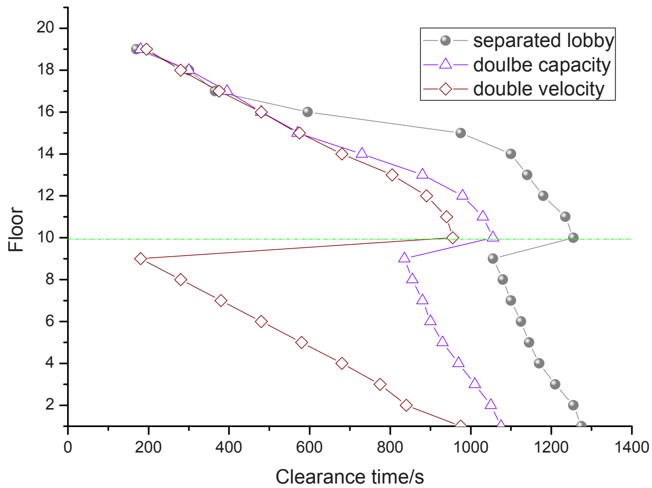

Fig. 5. Effect of elevator status on the clearance time of each floor of the office building.

As can be found in Fig.5, when the elevators move with faster speeds, the total evacuation time becomes much lesser than the separated lobby case in the former section. The evacuation process can be finished in about 18min. The evacuation process for the floors under the refuge floor becomes much more quickly, i.e., the clearance time becomes shorter. This can also be found from the number of people evacuated out of the building curve in Fig.6. The evacuation evolution process indicates that a faster elevator can transport more evacuees to safety zones. For those who locate above the refuge floors, the have to move firstly down to the refuge floor and then choose to evacuate by the elevator when the elevator is available, otherwise, they will move down using stairs.

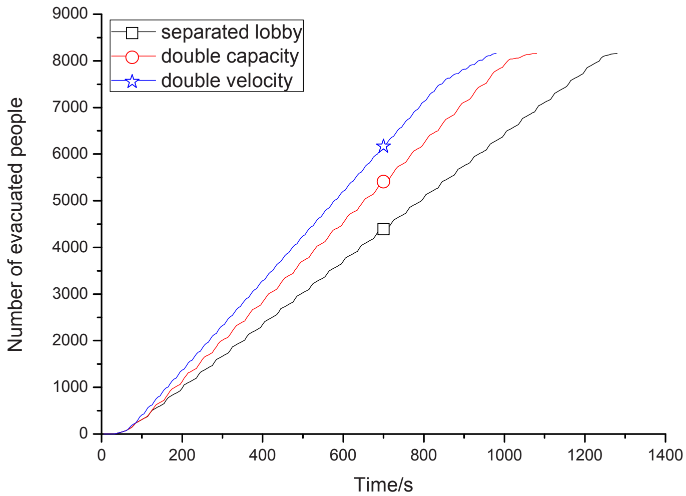

Fig. 6. Evacuation profile of the elevator aided evacuation under different elevator status situation.

When we further enlarge the elevator capacity, we can find in Fig.5 that the following interesting features. Firstly, the total evacuation time becomes about 16min, which is the shortest time to clear the lower section of the office building by only use stairs. Secondly, the clearance time for the upper section and the lower section becomes almost the same. That means there is nearly no evacuee move downward from the refuge floor using stairs. In other words, the elevators can transport all the pedestrians above the refuge floor on to the 1st floor in a fast way. Further improve the configuration of the elevators would not influence the total evacuation efficiency.

4. Conclusions

Aiming at improve the efficiency of building evacuation, well protected fire elevators are now proposed to be allowed to evacuate building occupants in performance based fire designs. When used to evacuate occupants, elevators cannot stop at each floor, which would definitely slow down the evacuation process. Thus based on a refuge floor elevator dispatch strategy, the influences of factors such as the number of people to be evacuated, the building plan arrangement, and the configuration of elevator status have been carefully detailed using a network model for building evacuation. Summarizing the numerical simulation results, a *first principle* for elevator aided evacuation scenario has been proposed, i.e., the fire elevator and the stairwell should not share a lobby on the floors to the safety zone. The dynamics of the elevator aided evacuation indicate there is a best evacuation situation where the efficiency is the highest, which means there is a *top limit of optimization* that elevators can provide when used as a way of escape. Under this situation, each of the sections divided by the refuge floor would be cleared at the same time. Further improve the elevator configuration would not improve the evacuation process.

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